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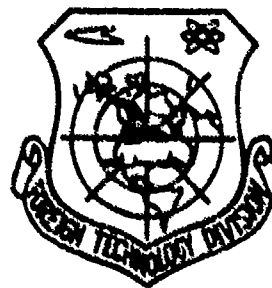
# FOREIGN TECHNOLOGY DIVISION



DEVELOPMENT OF HARD FILMED LASER MIRRORS

by

Gu Peifu and Tang Jinfa



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# EDITED TRANSLATION

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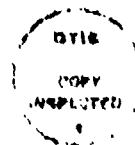
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DEVELOPMENT OF HARD FILMED LASER MIRRORS

(Original manuscript recieved November 11,1980)

Gu Peifu and Tang Jinfa

[Abstract] In this paper simple expressions are reported for predicting the optical losses of laser mirrors. Based on the standing wave dispersion in the mirrors, we have designed a low loss 23 layer hard film mirror. The major features of this design are that the high refractive index films are made of a mixture of  $\text{TiO}_2$  and  $\text{ZrO}_2$ , and that one or two optimum film pairs are added to the design. It is possible to produce an excellent hard film mirror using ordinary technology which has a loss of less than 0.2% and a reflective index higher than 99.8%.

## Foreward

The laser mirror is the most important basic part of any laser instrument. In recent years mirrors have attracted extraordinary interest as a research topic. There are two important dimensions to the purpose of this research: the first is to heighten the index of reflection of the mirrors in order to increase the export work ratio of laser instruments, the second is to improve the mirror's firmness and stability and thus extend the useful life of the laser.

On the basis of our research with soft film mirrors we have made progress towards expanding the work of developing hard film mirrors. Hard film mirrors not only have good chemical stability and mechanical firmness, there is reason to hope that the reflection indices will surpass those of soft film mirrors. Because of this we can successfully prepare a mirror that can both react well to temperature to bear the low melting point of glass and achieve an excellent reflection index higher than 99.8%.

## I. OPTICAL LOSS OF THE MIRROR

The pivotal question when making high quality hard film mirrors is still how to reduce the optical loss of the mirror [1]. The optical loss of the mirror can be divided into absorption loss, scattering loss, and penetration loss. Penetration loss can often be decreased by sending the light through many built up film layers; controlling the losses due to absorption and scattering, however, is far from easy.

### Absorption

According to Poynting's theorem, we know the absorption loss inside the film layers is exactly proportional to  $nE^2$  where  $n$  is the refractive index of the film layers and  $E^2$  is the average electric field strength. If the absorption coefficient of the film is sufficiently small, then the volume absorption produced by the high refractive index layer of the  $i^{\text{th}}$  film pair in the mirror is [2]

$$A_H^{(i)} = \beta_H d_H (n_H \bar{E}_i^2 / E_0^2)$$

In the formula  $n_H d_H = \frac{\lambda}{4}$ ,  $\lambda$  is the entering wavelength,  $\beta_H$  is the absorption coefficient of the high refractive index film layer,  $E_0^2$  is the electric field strength of the entering wave, average electric field  $\bar{E}_i = E_{i,\dots} / \sqrt{2}$ , according to the high reflecting mirror standing wave dispersion shown in Fig.1. It is not hard to see  $E_{i,\dots} = \left( \frac{n_L}{n_H} \right)^i 2E$ . In the same way, we can find the volume absorption  $A_L^{(i)}$  for the low refractive index layer of the  $i^{\text{th}}$  film pair. Therefore the volume absorption for the  $i^{\text{th}}$  film pair is

$$A_V^{(i)} = A_H^{(i)} + A_L^{(i)} = \frac{\lambda}{2} (\beta_H + \beta_L) \frac{1}{n_H^i} \left( \frac{n_L}{n_H} \right)^{2i}$$

To arrive at the volume absorption for the entire mirror we

need only solve for N film pairs to get

$$A_v = \frac{\lambda}{2} (\beta_H + \beta_L) \frac{1}{n_H^2} \sum_{i=0}^N \left( \frac{n_L}{n_H} \right)^{2i}$$

If N is sufficiently large, we can approximate the above equation as

$$A_{v \dots} \approx \frac{\lambda}{2} (\beta_H + \beta_L) \frac{1}{n_H^2 - n_L^2},$$

and under conditions where N is not large it can be analogously expressed as

$$\begin{aligned} A_v &= \frac{\lambda}{2} (\beta_H + \beta_L) \frac{1}{n_H^2 - n_L^2} \left[ 1 - \left( \frac{n_L}{n_H} \right)^{2N+2} \right] \\ &= \frac{2\pi(K_H + K_L)}{n_H^2 - n_L^2} \left[ 1 - \left( \frac{n_L}{n_H} \right)^{2N+2} \right] \quad (1) \end{aligned}$$

The above equation is then the volume absorption on the laser wavelength for the film system specified in Fig.1.

The most recent research has clearly shown<sup>[3]</sup> that there is a surface absorption in the mirror aside from the volume absorption. Such surface absorption is sometimes large enough to equal thin film volume absorption. Experimental techniques to differentiate thin film surface absorption and volume absorption have already been developed.

Inside the laser mirror, surface absorption originates at the HL boundary. We know that the electrical field strength at the laser mirror exterior surface and at each LH boundary is very weak. For this reason the effect of contamination at these boundaries on the performance of the film layers is of no importance. However, because the electrical field strengths at the HL boundaries are maximum values, contamination, no matter how minor, cannot be ignored. The surface

absorption at the HL boundaries can be calculated using a method similar to that used for the volume absorption; we need only select the electric field maximum  $E_{i, \max}$  rather than the electric field average  $\bar{E}_i$ . Due to the fact that the optical thickness on the two sides is very small, we can also effectively treat the electric field as a constant. In this way the surface absorption at the  $i^{\text{th}}$  HL boundary  $A_i^{(1)}$  can be expressed as

$$A_i^{(1)} = A_{HL} \left( \frac{E_{i, \max}}{E_0} \right)^2$$

$A_{HL}$  in this equation is the unit electrical field surface absorption on the HL boundary where the optical thickness is very small, and

$$A_{HL} = \int_0^d n_H \beta_H' d(d_H) + \int_0^d n_L \beta_L' d(d_L)$$

The division between  $\beta_H'$  and  $\beta_L'$  is the surface absorption coefficients of the high and low refractive index films. The surface absorption of the entire mirror is then

$$A_{1, \dots, N} \approx 4A_{HL} (n_H^2 - n_L^2)^{-1}$$

Under conditions where film pairs are limited we have

$$A_1 = 4A_{HL} \frac{1}{n_H^2 - n_L^2} \left[ 1 - \left( \frac{n_L}{n_H} \right)^{2N+1} \right] \quad (2)$$

This then, is the surface absorption on the above described specific mirror of the laser wavelength.

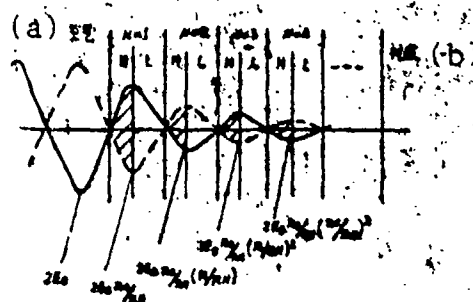


Fig.1 Standing waves in the mirror. Key. (a)Air; (b) Base.



## Scattering Losses

Scattering loss includes volume scattering and surface scattering. The former is due to the imperfections of the interior structure of the thin film such as the crystal structure of the film, sprinklings of grains caused by evaporation, and small dust particles, split lines, and pock marks in the film layers. The latter is caused by irregularities in the thin film boundaries and the coarseness of the surfaces; it is the sum of reflections due to the coarseness of the base plate, the cylindrical structure, impurities in the film and so on.

Four different models have already been proposed to describe a theory of scattering. The first model is the "Unevenness of volume" model. This model is directly related to the cylindrical structure of the film, the concept of 'true' density and so on. The second model is called the "Relative surface coarseness" model. This model assumes the microscopically observed coarseness at the base reappears in original form at each film boundary; that is to say the coarseness of each boundary surface is completely related. The third model is called the "Non-relative surface coarseness" model. This model is the exact opposite of the first model; the surface coarseness of each thin film boundary is determined by the individual surface with no interrelation. The fourth model is the "Partially related surface coarseness" model. This model is actually a combination of the two models two and three. As this type of model points out, the microscopically observed coarseness of the base can, on the one hand, reappear on each of the thin film boundaries, while on the other hand each boundary can introduce new additional coarseness. Obviously, if the additional coarseness is discounted, this kind of model is then actually the original

second model. Each of the models described above can be described using either vector scattering theories or scalar scattering theories. For the former, it is important to research for all types of angles information of relative light position and polarizing effect, and for the latter it is important to research the scattering energy.

The above described models offer convenience for our scattering research and we can make use of each model according to the actual measured unevenness of volume and surface coarseness, calculating the volume scattering and surface scattering separately. Here, we only want to discuss simply the scattering loss on the laser mirror laser wavelength.

We considered that the volume scattering makes the penetration ratio decrease according to the index number law; because of this we can arrive at an expression for volume scattering loss as we did for volume absorption:

$$S_{v, \dots} = \frac{2\pi(K_H' + K_L')}{n_H^2 - n_L^2}$$

The  $K_H'$  and  $K_L'$  of the equation are defined as the volume scattering light extinction coefficients for high and low refraction index film layers. For mirrors with few layers, the volume scattering is expressed as

$$S_v = \frac{2\pi(K_H' + K_L')}{n_H^2 - n_L^2} \left[ 1 - \left( \frac{n_L}{n_H} \right)^{2N+1} \right] \quad (3)$$

The important thing to find for surface scattering is the surface average root coarseness<sup>0</sup>. In view of the fact that the standing wave strength on the LH boundary is very small, we can ignore the contribution of the surface scattering, and the scattering on the HL boundary then offers sufficient weight. The scattering at the  $i^{\text{th}}$  HL boundary

can be expressed as

$$S_i^{(1)} = \alpha_i \frac{n_H E_{i,1,2}}{E_i^2}$$

$\alpha_i$  is the boundary constant<sup>[1]</sup>,  $\alpha_i = 8\pi^2 (n_H - n_L)^2 \left(\frac{\sigma_i}{\lambda}\right)^2$ .

Now assume each boundary is related; since  $\sigma$  does not change, and  $\sigma \ll \lambda$ , then when it enters perpendicularly, the loss for the surface scattering over the entire mirror is

$$S_{s.s.} \approx 32\pi^2 n_H \left(\frac{n_H - n_L}{n_H + n_L}\right) \left(\frac{\sigma}{\lambda}\right)^2$$

In the same manner, when there are few layers it is expressed as

$$S_i = 32\pi^2 n_H \left(\frac{n_H - n_L}{n_H + n_L}\right) \left(\frac{\sigma}{\lambda}\right)^2 \left[1 - \left(\frac{n_L}{n_H}\right)^{2N+1}\right] \quad (4)$$

Equations (1)-(4) constitute the sum of the loss for the entire mirror, and

$$L = \left[ 2\pi (K_H + K_L + K_H' + K_L') + 4A_{HL} + 32\pi^2 n_H (n_H - n_L)^2 \left(\frac{\sigma}{\lambda}\right)^2 \right] \frac{1}{n_H^2 - n_L^2} \left[ 1 - \left(\frac{n_L}{n_H}\right)^{2N+1} \right]$$

This equation is applicable not only for highly reflective mirrors, but also for few layered low reflecting mirrors as well. The above formula clearly shows, if the loss is to be reduced as much as possible, the important thing is to decrease the light extinction coefficient and surface coarseness for the film layers, and, in order to achieve a high reflection index, there is actually not much leeway for regulating the film layer refraction index and film layer number.

## II. DESIGN OF THE MIRROR

In view of the above discussion, when designing mirrors, regardless of whether it's choosing film materials or constituting film systems, we must try to reduce the effects of the light extinction coefficient and surface coarseness to get the highest reflection index possible.

### Thin Film Materials

Usually, the materials used to prepare hard film mirrors are a group of highly transparent, high temperature oxides. For high refractive index material,  $\text{TiO}_2$  and  $\text{ZrO}_2$  are often used, and  $\text{SiO}_2$  is often used as a low refractive index material. Table 1 shows the similar optical constants of these materials. It can be seen from the chart that the refractive index for the high refractive index material  $\text{ZrO}_2$  is surprisingly low; when it is constituted with  $\text{SiO}_2$  into a highly reflective mirror, it requires at least 27 layers. Often, however, as the number of layers increases, the additional surface coarseness also get larger. One tested way to deal with additional surface coarseness is to make use of a many layered film with an optical thickness of  $\frac{\lambda}{2}$ , because the electrical field strength of this type of film system is equal at every boundary. For this reason the scattering at each demarcation from the air side to the base side is almost identical and the overall scattering is the sum of that from each boundary. It is quite simple to make use of this technique to fix the slow increase in the additional coarseness. Usually, the added coarseness of each layer is about 5-10% of the coarseness of the base. This illustrates clearly why it is not appropriate to use  $\text{ZrO}_2$  as the high refraction index material. The refractive index of  $\text{TiO}_2$  film can reach 2.25-2.3; usually the reflective requirement can be satisfied with only 21 layers. Obviously, from the point of view of refractive indices, using  $\text{TiO}_2/\text{SiO}_2$  is more beneficial than

refractive indices, using  $\text{TiO}_2/\text{SiO}_2$  is more beneficial than using  $\text{ZrO}_2/\text{SiO}_2$ .

We will now look at the light extinction coefficient. Table 1 shows the light extinction coefficient for the high refractive index materials will be much larger than that of the low refractive index materials. The  $\text{TiO}_2$  light extinction coefficient is the largest, and it obviously depends upon the oxygen pressure in a vacuum room. If we choose a  $\text{TiO}_2/\text{SiO}_2$  film system then from equation (1) we get the approximate value for the absorption in a non-oxygenated environment, close to  $A_v = 0.14\%$ . The absorption for a  $\text{ZrO}_2/\text{SiO}_2$  film system is  $A_v = 0.05\%$ . It can be seen that the absorption loss for  $\text{TiO}_2/\text{SiO}_2$  is too large. This is precisely  $\text{TiO}_2$ 's drawback.

TABLE 1

(a) 材料	(b) 折射率 n	消光系数 k (c)
$\text{TiO}_2$ (d) 不充氧	2.25~2.30	$\sim 6.5 \times 10^{-4}$
(e) 充氧		$\sim 4.0 \times 10^{-4}$
$\text{ZrO}_2$ (d) 不充氧	1.95	$\sim 1.3 \times 10^{-4}$
(e) 充氧		$\sim 1.5 \times 10^{-4}$
$\text{SiO}_2$ (d) 不充氧	1.46	$\sim 1.2 \times 10^{-5}$
(e) 充氧		$\sim 1.0 \times 10^{-5}$

Key: (a) Material; (b) Refractive index n; (c) Light extinction coefficient k; (d) Unxygenated; (e) Oxygenated.

has a minimum 'true' density. On the one hand it makes the film layers produce additional coarseness, on the other, it leads to maximal scattering, the effect on the high refractive index materials becomes especially large. This is because the refractive index of the high refractive index materials' pore side boundary and nuclear space has a very large error; even after it has absorbed enough water it is still like this. Therefore one of the standards in choosing the material

From the thin film

structure we see, as everyone knows, the maximum number medium value thin film all appear cylindrical in structure; the cylindrical form and size differ according to the material, and is further closely related to technological preparation. Thin film of this kind of cylindrical structure often

is the unevenness or defects inside the film. Supposing the selection is logical, then it can be hoped that the volume scattering will appear smaller than the surface scattering. One easy method of testing the volume scattering of the materials is to deposit a gradually thickened layer of film on the base and then afterwards to look and see if the scattering has increased or if it remains the same. If the scattering is almost unchanged it shows that the scattering is not enough to talk about. For  $\text{SiO}_2$  the film layers are without definite structure with a true density approaching 1. Without a doubt it is fully satisfactory for use as a low refractive index material. As for the high refractive index materials,  $\text{ZrO}_2$  often shows a negative refractive index unevenness; as the thickness of the film increases the refractive index is gradually reduced. The testing method for this kind of refractive index unevenness, as Fig.2 shows, takes the film layers to be tested and plates them on a plane of low refractive index glass, straight till  $\lambda$ , appears the smallest reflective index then stops. If the film layer is even, then for  $\lambda_0$ , there is  $R_{\text{with film}} = R_{\text{without film}}$ , and the opposite, if the film layer shows a negative unevenness then  $R_{\text{without film}} > R_{\text{with film}}$ ; if it shows positive unevenness then  $R_{\text{with film}} > R_{\text{without film}}$  (See part a of Fig.2). Part b of Fig.2 is the change in refractive index of the response, c is the three cylindrical models of the response. Using elliptically polarized light to measure this kind of unevenness results in extraordinary accurate measurement. Analysis clearly shows  $\text{ZrO}_2$  film tends to produce high volume scattering. The density of  $\text{TiO}_2$  film, it can be hoped, will approach 1, rather effective for controlling volume scattering.

Stress on the thin film not only makes the base board produce deformation, it also makes the scattering of the film increase. Therefore another standard for selecting film material is to ensure that the mirror has the lowest possible

stress. This means that the stress on both the high and low refractive index materials will be sufficiently small, and the stress characteristics must be opposite so that the connection stress decreases. But unfortunately both  $ZrO_2$  and  $SiO_2$  have tensile strength, and the stress value is very large. With back temperatures at  $100^\circ C$ , they are each  $2500Kg/cm^2$  and  $2000Kg/cm^2$ .

It is for precisely this reason that  $ZrO_2/SiO_2$  many layered film sometimes has cracks appear; even when the film layer is not yet actually cracked it breaks the film layer structure even to the point of producing splits thus making the scattering increase several times.  $TiO_2$  film, the opposite of  $ZrO_2$  film, exhibits pressure stress, so this creates a condition in order to reduce stress on the mirror.

To sum up, neither  $ZrO_2$  nor  $TiO_2$  is really satisfactory for hard film mirror material. Of the two,  $TiO_2$ 's important shortcoming is its serious decomposition, very large volume absorption, its other characteristics are comparatively good. Is it then possible to reduce the decomposition? Yes. If a certain kind of metal or oxide is placed in the oxide materials during the vaporization change, then we can hope to obtain a low absorption oxide film. On the basis of this kind of thinking, we take  $TiO_2$  and  $ZrO_2$  and mix it up to proceed with the vaporization as the oxidation promoting function of  $ZrO_2$  controls the  $TiO_2$  film's high temperature decomposition.

We experimented with  $TiO_2$  and  $ZrO_2$  mixes of different proportions. With the aid of elliptically polarized light

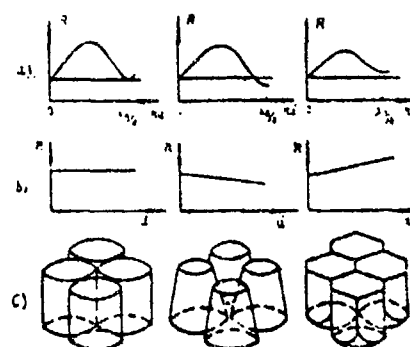


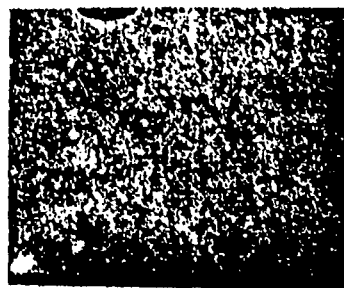
Fig.2 Uneven film and cylindrical structure.

we measured the refractive indices for each type of mix. Among them the refractive index for the 1:1 mix was in the range of 2.1~2.15, according to the measured refractive index value, we selected 23 or 25 layers as the number of layers in the film.

Structural research shows, at base temperatures of 200°C, the mix film appears to be without a defined structure (photograph 1). Comparing the mirror prepared using the mix film (photograph 2) with a  $\text{ZrO}_2/\text{SiO}_2$  mirror (photograph 3), it is seen that the surface is comparatively fine and smooth, and coarseness is obviously lowered. Photograph 4 is the cross section of the microscopic structure of the mix prepared mirror; compared to the cross section microscopic structure of the  $\text{ZrO}_2/\text{SiO}_2$  mirror in photograph 5 the fineness of the mix film is positively inspiring.



Photograph 1  
1:1 mix film electric  
diffraction graph-base  
temperature 180°-200°C.



Photograph 2  
Electron micrograph  
(25000X) of  $(\text{TiO}_2-$   
 $\text{ZrO}_2)/\text{SiO}_2$  23 layer  
mirror.

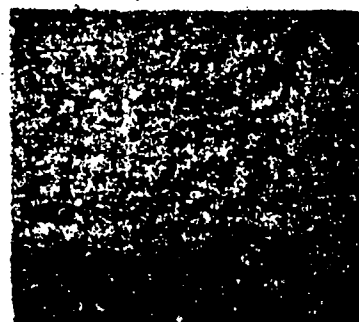


Photograph 3  
Electron micro-  
graph (25000X)  
of  $\text{ZrO}_2/\text{SiO}_2$  25  
layer mirror.





Photograph 4  
Cross section microscopic  
structure of 15 layer  $(\text{TiO}_2\text{-ZrO}_2)/\text{SiO}_2$  mirror. (25000X)



Photograph 5  
Cross section microscopic  
structure of 25 layer  
 $\text{ZrO}_2/\text{SiO}_2$  mirror. (25000X)

### Control Wavelength

Calculating from the strength of the standing wave of the mirror we can see that, for wavelength ranges larger than the center wavelength, the standing wave loop stands in the middle of the high refractive index layer and, the reverse, the standing wave loop falls in the low refractive index film (Fig.3). As  $K_H \gg K_L$ , the spectrum absorption curve and corresponding reflection curve appear obviously unsymmetrical, and the minimum absorption ratio and maximum reflection ratio positions also move toward short wave. Fig.4 is the spectrum absorption curve and reflection curve of the  $\text{TiO}_2\text{-ZrO}_2/\text{SiO}_2$  mirror. From the figure we can see the absorption curve is

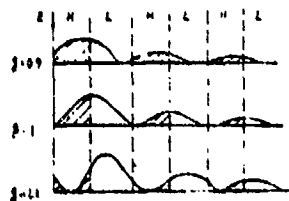


Fig.3 Standing wave dispersion for the mirror at different wavelengths.

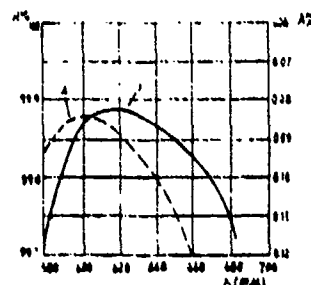


Fig.4 Spectrum absorption curve for  $G(\text{HL})^{11}\text{HA}$  film system.

$$n_H = 2.15(\text{ZrO}_2 - \text{TiO}_2), \quad n_L = 1.46(\text{SiO}_2)$$

$$K_H = 3.6 \times 10^{-4}, \quad K_L = 1.2 \times 10^3, \quad \lambda_0 = 0.633 \mu$$

is greatly removed from the center wavelength, the separation at times reaching 5-10%; the mirror absorption curve shown in Fig.4 is actually separated by 5%. The shortening of the absorption curve resulted in the shortening of the maximum reflection index. The maximum reflection index in the figure is actually shortened close to  $200\text{\AA}$ . If there are even more layers, then the maximum reflective index and maximum absorption index get closer; the shortening of the reflective index is even greater. This means the control wavelength of the mirror should move appropriately toward the longer wavelengths about  $200\text{\AA}$ , making the center wavelength  $0.633\mu$  just exactly fall in the area of minimum absorption and on the wavelength of maximum reflection ratio. What we should point out is, if the outermost pair (or pairs) of high refractive index layers get thinner and the low refractive index layers are thickened, then the appearance of this kind of shortening phenomenon is reduced.

#### Improving the Film System

Because of the standing wave dispersion of the mirror, we made two improvements to the film system. The first improvement was to use  $\text{ZrO}_2$  as a substitute for the outermost two pairs of high refractive index layers in the film on the air side and not to use  $(\text{TiO}_2\text{-ZrO}_2)$  film layers. The benefit of doing it this way lies, on the one hand, in that we can hope for a reduction in absorption if we properly place the  $\text{ZrO}_2$  film with the lowest light extinction coefficient at the position of maximum standing wave strength, and on the other hand, in that Helium-Neon laser mirrors often require that they be sealed in a low gas pressure laser instrument, and when  $\text{TiO}_2$  film is exposed under minimum gas pressure, and the temperature exceeds  $200^\circ\text{C}$  it causes an obvious increase in loss. The reason for this is that decomposition appears in the  $\text{TiO}_2$  outer layer of the film pile,

consequently leading to a lowering of the reflection index. Of course this kind of effect is not found in the air. From this point of view  $\text{ZrO}_2$  film has the additional function of protecting the film. The second improvement is to increase the  $\text{SiO}_2$  film thickness and decrease the  $\text{ZrO}_2$  film thickness in the last air side pair of film layers. This is done because the light extinction coefficient for  $\text{SiO}_2$  is smaller by one quantity level than the light extinction coefficient for  $\text{ZrO}_2$ . When the  $\text{SiO}_2$  film is thickened the standing wave loop falls in the low refractive index film layer with the low light extinction coefficient and thus lowers absorption. At the same time, because the electrical field strength at the boundaries correspondingly decreases, we can hope to achieve a reduction in the scattering.

Optical thickness of  
high refractive index.

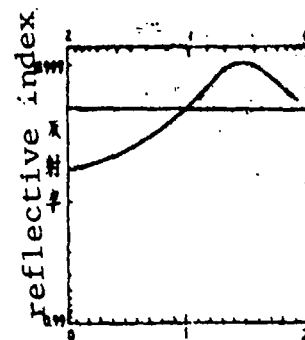


Fig.5 Reflection index change after adding an optimum pair at  $\frac{\lambda}{4}$  pile.

Figure 5 shows the change in reflection index after the outermost pair of high-low refractive index film layers is added onto a  $1/4$  wave pile of a mirror which has already arrived at the maximum value reflection index. The horizontal line on the chart represents the maximum reflection index attainable by the  $\frac{\lambda}{4}$  pile, the bottom of the chart is the optical thickness of the low refractive index layer and the top has the optical thickness of the high refractive index layer; it exactly makes the relative motion of the coming together of the two layers of film  $\pi$ . As can be seen from the chart, with the low refractive index layer near  $1.42 \times \frac{\lambda}{4}$  and the high refractive index near  $0.7 \times \frac{\lambda}{4}$ , the reflection index increases to its greatest value. We call this type of film pair the optimum film pair; the optimum film pair design has great effect in decreasing the absorption

loss for the mirror. Comparing this to other design methods<sup>[5]</sup> it achieves the highest reflection index with the fewest layers. Without a doubt, it also has many advantages for decreasing the scattering in the mirror

One important way for reducing surface scattering is to use an uneven film design. Fig.6a is the  $n|E|^2$  dispersion and refractive index dispersion for the last few pairs of film in the mirror. As the refractive indices on the HL boundaries are non-continuous  $n|E|^2$  is also discontinuous; its refractive index difference  $\Delta n = n_H - n_L$  assumes a square period change. Now if we add a layer of uneven film with gradually changing refractive index outside the wave pile with the index changing from 2.1 at the air side to 1.46 where the optical thickness is  $\frac{\lambda}{2}$  (Fig.6b), as the loop position boundary disappears, so the loop electric field strength does not reappear to function. Calculation clearly shows, surface scattering can drop below 51%. Of course, because the depth of the electric field penetration increases volume absorption and volume scattering may perhaps show a slight increase. Regardless of how it is, this type of design for reducing scattering and raising the value for laser resistance to separation is very meaningful. In view of the difficulties of preparing uneven films, at present we do not yet employ them.

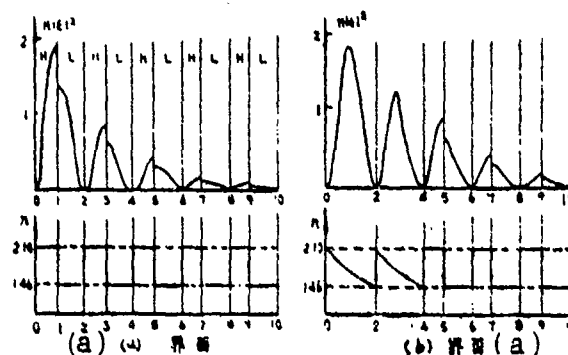


Fig.6  $n|E|^2$  & refractive index dispersion for  $\frac{\lambda}{4}$  pile and two-layer uneven film.  $\frac{\lambda}{4}$   
Key: (a) Boundary.

To finish, we can write out the complete design of the

mirror which is

$$G1.02 | (HL)^9 HLH' 1.42 L 0.7H' | A$$

where  $H \text{---} (TiO_2 - ZrO_2)$ ,  $H' \text{---} ZrO_2$ ,  $L \text{---} SiO_2$ ,  $\lambda_0 = 633m\mu$ .

The above described mirror has an extremely small loss. Figure 7 is the spectrum absorption curve of the above described mirror, and compared against figure 4, it is easily seen that, with equal numbers of layers, the level of the highest reflective index is raised while absorption is reduced. If we add another optimum pair of film layers to this newly designed film system, then we can raise the reflective index even higher; however, for the mirror indicated in figure 4, to rely on increasing the layers to raise the reflective index is of no avail.

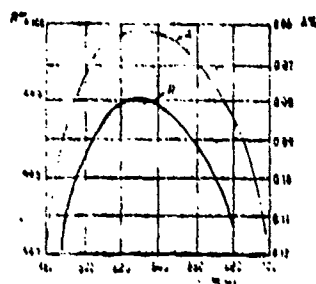


Fig.7 The spectrum absorption curve and reflection curve of new design  
 $G1.02 | (HL)^9 HLH' 1.42$   
 $L 0.7H' | A$

$$n_H = 2.15(ZrO_2 - TiO_2)$$

$$n_L = 1.46(SiO_2)$$

$$n_{H'} = 1.95(ZrO_2)$$

$$K_H = 3.6 \times 10^{-4}$$

$$K_L = 1.2 \times 10^{-6}$$

$$K_{H'} = 1.3 \times 10^{-4} \quad \lambda_0 = 0.633\mu$$

### III. THE PREPARATION OF THE MIRROR

After the low loss mirror was designed, we wanted to assure that technology could attain the ideal result. The slightest amount of carelessness in crafting could spoil all the previous efforts to achieve the optimum design. Therefore, when considering each step of production, we had to concentrate on the crucial concern of how to control absorption scattering loss.

Our experiments were carried out on the Beijing instrument factory DMD-450 multi-layered plated film machine; here we described simply several essential factors as follows:

#### Base Plate Quality

The quality of the base plate is crucial to reducing surface scattering. There are usually two things required of the base. The first is the surface coarseness: obviously, if the base surface scattering is already larger than 0.2% then it will be impossible to arrive at a 99.8% reflective index. Experiment has shown the purity of light for the base plate must be better than class I, so when casting the light the appropriate light casting techniques must be observed to reduce the surface coarseness. The second requirement is the cleanliness of the base plate. The rubbing of the base plate must be thoroughly careful; one must not damage the base plate and must guarantee that the surface is sufficiently clean. Aside from this we must also ensure that the vacuum is clean and must also render the necessary care during the operation and put an end to all the illogical operation which might possibly contaminate the base plate.

When light enters perpendicularly, the accumulated scattering caused by surface coarseness of the base plate is

$$S = 1 - \frac{R}{R_0} = 1 - \exp \left[ - \left( \frac{4\pi\sigma}{\lambda} \right)^2 \right] \approx \left( \frac{4\pi\sigma}{\lambda} \right)^2 \quad (5)$$

$R$  in the mirror direction reflective index for the coarse surface,  $R_0$  is the smooth surface reflective index,  $\sigma$  is the base plate surface average root coarseness. As the base plate volume scattering is sufficient to neglect, the sum scattering for the base plate can be measured in a short time. The surface coarseness can then be determined conveniently using the formula below. The surface quality of

the base plate can thus be evaluated simply and effectively with this method.

$$\sigma = \lambda (R_0 - R)^{\frac{1}{2}} / 4\pi R_0^{\frac{1}{2}}$$

Figure 8 is the relation between the scattering and  $\sigma$  as calculated according to equation (5). We can see from the chart, if a reflection index higher than 99.8% is to be attained, the average square root coarseness of the base plate must be less than  $20\text{\AA}$ , but actually, using the usual light casting techniques,  $\sigma > 20\text{\AA}$  is commonly attained. This only requires the mirror base casting of light adopt specified steps.

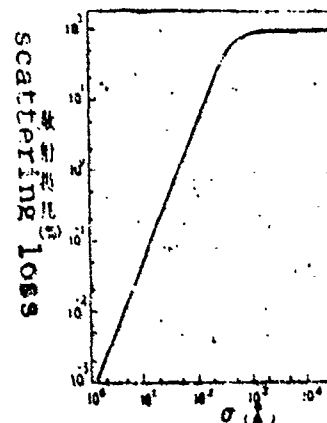


Fig. 8. The relationship between scattering loss and root mean square roughness.

#### Deposition Parameter

In order to get a low loss mirror, every effort must be made to find an appropriate deposition parameter. The vacuum degree is  $3 \sim 9 \times 10^{-5}$  millimeters, when vaporization has just begun, most vacuum levels decline greatly, in the process of vaporization the vacuum degree gradually rises. During the course of vaporization, base plate temperature, from start to finish, stays between  $180 \sim 200^\circ\text{C}$ . If the upper limit of base plate temperature is exceeded the scattering will increase. Typically, the electron beam vaporization parameter for the  $(\text{TiO}_2\text{-ZrO}_2)$  base material filament electric current is 13A, the voltage 8KV, and the beam current is 80mA. The deposition speed ratio is generally 20-30  $\text{\AA}/\text{second}$ ; quick vaporizing film layers have very high refraction indices, but the absorption is correspondingly increased.  $\text{ZrO}_2$  materials have a vapor-voltage of about 10KV, beam current of 100mA, and deposition

speed ratio of 30-40A/second. This clearly shows the mixed filament vaporizes more easily than the  $ZrO_2$ . To analyze the  $TiO_2$  and  $ZrO_2$  purely, take a 1:1 weight proportion and evenly mix with heat and pressure. When melting before the gas is eliminated the temperature must be slowly raised, when eliminating the gases the operation should proceed quickly, simultaneously making the material sprinkle filling the mirror with dots, and lowering the film refractive index. During the vaporization process, as the layers are increased, the remaining  $ZrO_2$  is added to the film material; however, this situation is, exactly what is needed for the mirror, as the closer to the outside the film layer is, the lower the light extinction coefficient requirement becomes.

#### Thickness Control

Because the increase in layers leads to an increase in the surface coarseness, we must use the smallest number of layers to obtain the highest reflective index. This means we must raise the thickness of the film and control precision. We use penetrating light to directly control the plating of the 23 layers, so that film thickness error is automatically compensated for. In order to minimize the effects of stray light, and cause the wave length to shorten, except when the narrow crack of simple color instruments is sufficiently small, we also need to add a piece of low background interference filter before the narrow crack where simple color light enters. Thus we can basically eliminate the effects of stray light. To heighten the accuracy of reading numbers we used a compensating chart to read the numbers, and took sufficient care when controlling it.

When controlling thickness, the film layers on the base plate side need accurate control, but the outer few air side layer pairs do not require such accuracy. There is one



principle which should be kept in mind: the low refractive index layer should pass correctly and cannot be insufficient, and, the reverse, the high refractive index layer should be thin, not thick.

#### Handling the Baking

For any hard film mirrors of this type with either few or many layers, there exists some absorption caused by decomposition. In order to improve the decrease in absorption loss, it is absolutely necessary to bake it in air. The baking temperature is generally  $250^{\circ}\text{C}$ ; after two hours of baking, the reflection ratio shows an obvious increase. This explains the decrease in absorption. If the baking period is even longer, or the temperature is even higher, the effect is even better. From concerns arising from actual use, we generally bake at  $500\text{--}550^{\circ}\text{C}$ ; afterwards, although a slight increase in scattering is observed, still the absorption is lowered. The difference between reflective index of this mirror and the mirror baked at  $250^{\circ}\text{C}$  is therefore quite small. However, the result of the high temperature treatment is to make the durability even better. Experiment did show, however, that if after the mirror is fully bathed in air it is again baked at high temperature, the scattering may show an increase. This means that before the mirror is baked, the mirror should not be left in the air too long.

#### IV. CONCLUSION

Absorption and scattering loss in laser mirrors has been limited, and the reflective index has been heightened. This paper gives equations which approximately express calculations of optical loss of mirrors, discusses ways to reduce loss and raise the reflective index. In view of the standing wave dispersion in the mirror, we designed a type of low loss hard

film mirror. Its two main special features are that it makes use of a  $\text{TiO}_2$  and  $\text{ZrO}_2$  mix as material for the high refractive index film and adds one (or two) optimum film layer pairs into the film system. The structure of the mix is finer than  $\text{ZrO}_2$ , absorption is less than  $\text{TiO}_2$ , the refractive index satisfies requirements of the system, and vaporization is easy. The optimum film pair design can effectively control absorption loss; thickness control also is not a problem. Using this kind of logical design, and selecting appropriate production technology, it is not difficult to produce a low loss mirror. We used the ordinary straight gun on the DMD-450 plated film machine produced by the Beijing instrument factory, and for the vacuum chamber do not need an oxygenated environment. We only need to select the usual preparation techniques to be able to steadily achieve a mirror with a loss of less than 0.2% and a reflective index higher than 99.8%.

In passing there is something that should be pointed out: we mention that  $\text{ZrO}_2$  and  $\text{TiO}_2$  have some drawbacks as thin film materials, but these are not such that they cannot be overcome. For example  $\text{TiO}_2$ 's decomposition absorption only requires the adoption of logical production methods. In the same way we can produce a high quality hard film mirror.

Aside from this we also did machine stability testing and chemical stability experiments with the hard film mirrors. These include forcefully rubbing the film with gauze, soaking for one day in concentrated hydrochloric acid, high temperature baking in a  $550^\circ\text{C}$  cyclopentadienyl phosphor oven, and boiling for half an hour in boiling water. Of these experiments, the last two were conclusive because stress often decides a mirror's durability and high temperature and boiling water experiments can quickly simulate the environmental conditions of actual use, and accurately reflect the conditions of stress of the film layers. Then within the

framework of these two experiments, the boiling water experiment is even harsher than the high temperature test; if the remaining stress is very large in the boiling water it is possible for the film to peel. We went through these experiments repeatedly to prove that although the stress of these two mirrors is not great, they can all undergo these two experiments and survive with the reflective index basically unchanged. Aside from this, the hard film mirror almost never experiences change; after leaving it for 11 months, no change in the reflective index could be detected. The preceding is enough to illustrate that the stability and firmness of the hard film mirror are very good indeed.

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